Review of New Rare Hadronic B-decay Results

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We present one new result from Belle and many new results from *BABAR* for rare hadronic B decays. These include measurements of decays involving baryons, a Dalitz plot analysis of the three-charged-kaon system, many new results for B decays to $\eta' X$ and ωX, and a limit for the decay $B \to a_1 \rho$. Measurements of the vector-vector decays $B \to \rho K^*$ and $B \to \omega K^*$ are helping to understand the value of the longitudinal polarization fraction for these $B \to VV$ decays.

1. Introduction

In this paper we cover dozens of new measurements of branching fractions, charge asymmetries and longitudinal polarization of rare hadronic decays of B mesons. We will summarize the new results and compare with previous results and theoretical expectations.

2. $\overline{B}^0 \to D^{*+}\omega\pi^-$

A new measurement from *BABAR* of the decay $\overline{B}^0 \to D^{*+}\omega\pi^-$ [1] is a test of factorization since the amplitude is related to the amplitude for the decay $\tau^- \to \omega\pi^-\nu_\tau$ [2] (see Fig. 1). Charge-conjugate decay modes are implied throughout this paper unless explicitly stated otherwise.

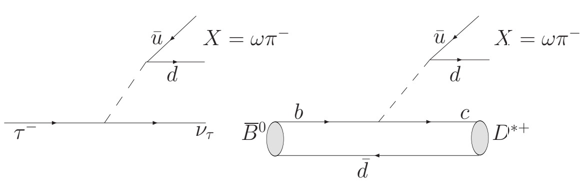

Figure 1: Feynman diagrams for $\tau^- \to \omega\pi^-\nu_\tau$ and $\overline{B}^0 \to D^{*+}\omega\pi^-$.

In Fig. 2, we show the normalized differential distribution for the $\omega\pi$ mass squared. We compare with the CLEO τ data [4] and a measurement by CLEO of the differential B decay spectrum [3]. There is good agreement with the CLEO data and the factorization expectation.

3. Decays with baryons

A variety of measurements of B decays to baryonic final states, until recently mostly by Belle, has challenged theoretical understanding of these decays. Issues such as threshold enhancements and angular correlation are still not completely understood. There are two new measurements from *BABAR* that will be discussed in the next sections.

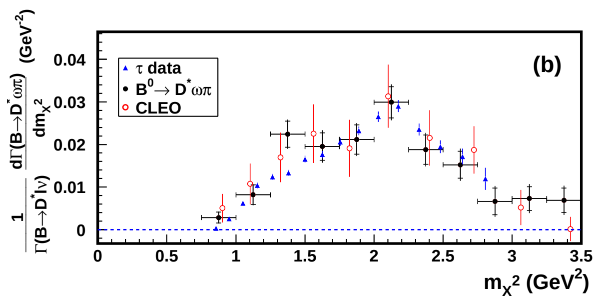

Figure 2: Data for the $\overline{B}^0 \to D^{*+}\omega\pi^-$ differential distribution of $\omega\pi$ mass squared, normalized to the semileptonic width $\Gamma(B \to D^*\ell\nu)$. The total error bars include the m_X^2-dependent systematic uncertainties but not a common 11.3% scale systematic uncertainty. Also shown are the predictions from CLEO τ data and the previous CLEO analysis of this B decay.

3.1. $\overline{B}^0 \to \Lambda_c^+ \bar{p}$

BABAR has measured the branching fraction for the decay $\overline{B}^0 \to \Lambda_c^+ \bar{p}$. They perform a maximum-likelihood (ML) fit to the quantities $m_{\rm ES}$ and ΔE, where $m_{\rm ES} \equiv \sqrt{(\frac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$ and the energy difference $\Delta E \equiv E_B^* - \frac{1}{2}\sqrt{s}$, where $(E_0, \mathbf{p}_0)$ and $(E_B, \mathbf{p}_B)$ are four-momenta of the $\Upsilon(4S)$ and the B candidate, respectively, and the asterisk denotes the $\Upsilon(4S)$ rest frame. The observed signal is 50.2 ± 8.4 events (see Fig. 3), leading to a branching fraction of $(2.15 \pm 0.36 \pm 0.13 \pm 0.56) \times 10^{-5}$, where the uncertainties are, respectively, statistical, systematic and in the $\Lambda_c^+ \to pK^-\pi^+$ branching fraction. This result is in good agreement with the published Belle measurement [5] and theoretical expectations [6].

3.2. $\overline{B}^0 \to \Lambda\bar{p}\pi^+$

Another new *BABAR* result is for the decay $\overline{B}^0 \to \Lambda\bar{p}\pi^+$. Again a ML fit to $m_{\rm ES}$ and ΔE is used to extract a signal of ~ 74 events leading to a branching fraction $(3.30 \pm 0.53 \pm 0.31) \times 10^{-6}$. Figure 4 shows the projections of the signal onto the $m_{\rm ES}$ and ΔE axes. Figure 5 shows that there is an enhancement near threshold in the $\Lambda\bar{p}$ mass. This feature is likely imp-

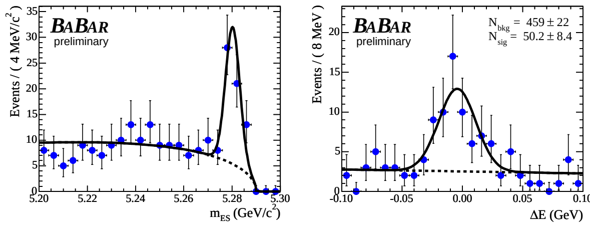

Figure 3: Projection plots of the $m_{\rm ES}$ and ΔE distributions for the $\overline{B}^0 \to \Lambda_c^+ \bar{p}$ analysis.

ortant in understanding the relatively large branching fraction for this decay [7, 8]. This measurement is also in good agreement with the published Belle result [9].

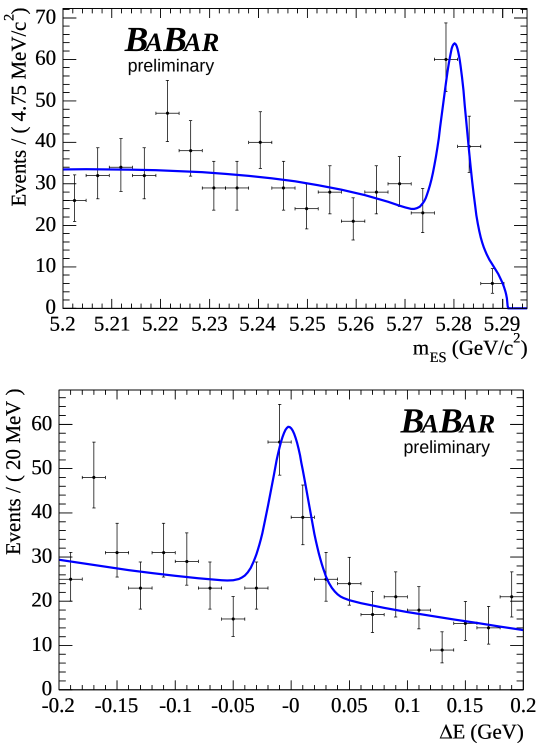

Figure 4: Projection plots of the $m_{\rm ES}$ and ΔE distributions for the $\overline{B}^0 \to \Lambda \bar{p} \pi^+$ analysis.

4. $B^+ \to K^+ K^- K^+$

The new *BABAR* measurement of the $B^+ \to K^+K^-K^+$ Dalitz plot has now been submitted for publication [10] so I will not go into the details here. The analysis includes contributions from the final states ϕK, $f0(980)K$, $f0(1710)K$, and $\chi_{c0}K$ and non-resonant as well as a channel denoted $X_0(1550)K$, previously seen by Belle [11], but not yet understood in terms of known resonances. The branching fraction for the three-charged-kaon state is measured to be $(35.2 \pm 0.9 \pm 1.6) \times 10^{-6}$, somewhat larger than,

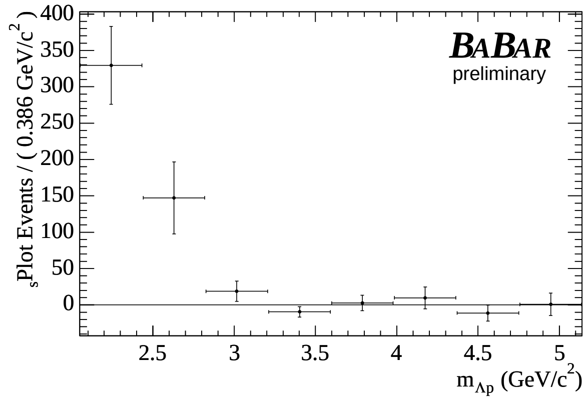

Figure 5: Plot of the $\Lambda\bar{p}$ invariant mass showing the enhancement at threshold.

but in agreement with the Belle result. The branching fractions for the various components of the Dalitz plot are measured. There is general agreement with Belle except that the width of the $X_0(1550)$ state is nearly twice as large in the *BABAR* analysis; this disagreement is not understood. The consequence is that the allocation of the branching fraction between $X_0(1550)K$ and the non-resonant component is different between the two analyses. Further progress will surely require a better understanding of the $X_0(1550)$ state.

5. New results involving η' mesons

The decay $B \to \eta' K$ was discovered nearly ten years ago by CLEO [12] with a branching fraction much larger than expected. This is more or less understood now as a result of a variety of enhancements including the effect of η/η' mixing [13] and those due to the leading order in $1/m_b$ [14]. More recently in a SCET calculation, this enhancement is identified with an additional term involving the gluonic content of the η' [15]. The prediction that the ηK channel is suppressed has been confirmed with fairly precise recent measurements [16, 17]. The situation for the other related decays is less clear. The pattern for the decays involving K^* mesons was originally thought to be reversed due to a sign flip involving a parity argument [13]. QCD factorization calculations [14] showed that the situation is more complicated with no sign flip for the usual QCD penguin amplitudes but a sign flip present for the $1/m_b$-suppressed non-$V-A$ amplitudes. The latter subtleties have not been widely recognized previously (including by the author in his verbal presentation in Vancouver). The result is that the decay $B \to \eta K^*$ is clearly enhanced but the suppression of the decay $B \to \eta' K^*$ involves the interplay between the two (opposite-sign) amplitudes mentioned above as well as possible contributions from flavor-singlet amplitudes. The fact that this decay being small is related to the abnormally large $1/m_b$-suppressed amplitudes was one of the less appreciated aspects of the QCD factorization calculations [14]. The non-strange decays involving a π or ρ meson are also interesting. New measurements of all of several of these decays are discussed in the following sections.

5.1. $B \to \eta' K^*$ and $B \to \eta' \rho$

BABAR has new results for the decays $B \to \eta' K^*$, $B \to \eta' \rho$, and $B^0 \to \eta' f_0$, where the latter is measured since it shares a common $\pi^+\pi^-$ final state with ρ^0. The η' mesons are reconstructed from the $\eta' \to \eta\pi^+\pi^-$ and $\eta' \to \rho^0\gamma$ decay modes and K^* mesons are reconstructed via $K^{*0} \to K^+\pi^-$, $K^{*+} \to K^+\pi^0$ and $K^{*+} \to K^0\pi^+$. ML fits are performed, with the variables $m_{\rm ES}$, ΔE, resonant masses (ρ or K^*), the ρ or K^* helicity angle, and a Fisher discriminant to distinguish signal from $q\overline{q}$ background primarily by event shape. The results for these fits are shown in Table I. The decay $B^0 \to \eta' K^{*0}$ is observed with a significance of 4.5 standard deviations (σ); the $m_{\rm ES}$ and ΔE projection plots for this mode are shown in Fig. 6. There is evidence for $B^+ \to \eta' K^{*+}$ at the 2.6σ level. However the branching fractions are small so there clearly is substantial suppression relative to the $B \to \eta K^*$ decays which have a branching fraction $\sim 20 \times 10^{-6}$ [18]. It seems that the $1/m_b$ terms must indeed be large for the suppression to be this large.

Table I Comparison of new *BABAR* results with previous results. Branching fractions ($\mathcal{B}$ in units of 10^{-6}), significance S and 90% C.L. upper limits (U.L.) where signal is not significant.

Mode	Previous results		New *BABAR* results		
	BABAR	Belle	$\mathcal{B}$	S	$\mathcal{B}$ U.L.
$\eta' K^{*0}$	< 7.6	< 20	$3.8 \pm 1.1 \pm 0.5$	$4.5\,\sigma$	
$\eta' K^{*+}$	< 14	< 90	$4.9^{+1.9}_{-1.7} \pm 0.8$	$3.6\,\sigma$	< 7.9
$\eta' \rho^0$	< 4.3	< 14	$0.4^{+1.2\,+1.6}_{-0.9\,-0.6}$	$0.3\,\sigma$	< 3.7
$\eta' \rho^+$	< 22	–	$6.8^{+3.2\,+3.9}_{-2.9\,-1.3}$	$2.3\,\sigma$	< 14
$\eta' f_0$	–	–	$0.1^{+0.6\,+0.9}_{-0.4\,-0.4}$	$0.2\,\sigma$	< 1.5

5.2. $B^+ \to \eta' \pi^+$ and $B^0 \to \eta' \pi^0$

Belle has updated the branching fraction measurements for $B \to \eta' K$ and $B^+ \to \eta' \pi^+$ and now also measure $B^0 \to \eta' \pi^0$ [19]. They perform ML fits to $m_{\rm ES}$ (called m_{bc} by Belle but it is the same quantity) and ΔE. The distributions of ΔE and $m_{\rm ES}$ are shown in Fig. 7. They find branching fractions for

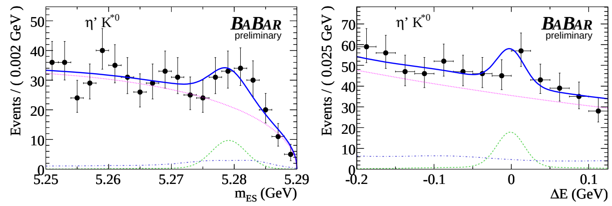

Figure 6: Projection plots of the $m_{\rm ES}$ and ΔE distributions for the $B^0 \to \eta' K^{*0}$ analysis.

$B^+ \to \eta' \pi^+$ of $(1.8^{+0.8}_{-0.7} \pm 0.1) \times 10^{-6}$ and for $B^0 \to \eta' \pi^0$ $(2.8 \pm 1.0 \pm 0.3) \times 10^{-6}$. The significance for the signals is 3.2 and 3.1σ, respectively.

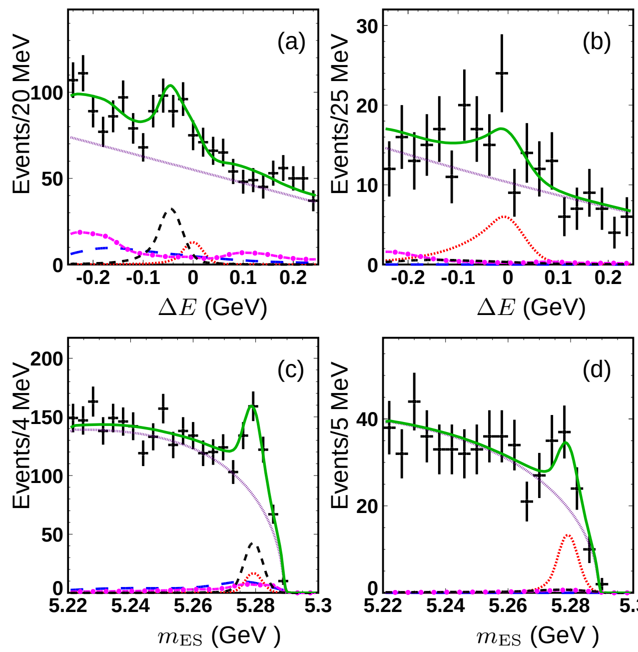

Figure 7: Distributions of ΔE for the Belle (a) $B^+ \to \eta' \pi^+$ and (b) $B^0 \to \eta' \pi^0$ analyses. Also $m_{\rm ES}$ for (c) $B^+ \to \eta' \pi^+$ and (d) $B^0 \to \eta' \pi^0$. The signal is shown as the red (dotted) curve and, for $B^+ \to \eta' \pi^+$, the crossfeed from $B^+ \to \eta' K^+$ is shown as the black dashed curve.

The new Belle branching fraction for $B^+ \to \eta' \pi^+$ is somewhat smaller than, but consistent with, the published observation from *BABAR*, $(4.0 \pm 0.8 \pm 0.4) \times 10^{-6}$ [16]. The situation for $B^0 \to \eta' \pi^0$ is reversed – the new Belle measurement is somewhat larger than the recently published measurement from *BABAR*, $(0.8^{+0.8}_{-0.6} \pm 0.1) \times 10^{-6}$ $(< 2.1 \times 10^{-6})$ [20]. While the world-average branching fraction for $B^0 \to \eta' \pi^0$ is not yet significant, it seems that this channel too may be close to observation at about the expected rate. This is interesting since the penguin for this mode is expected to be small and the color-suppressed tree amplitude is also expected to be strongly suppressed [21].

6. Charmless Vector-Vector decays

The decays of a B meson to pairs of vector particles are interesting for a variety of reasons. Early interest focused on issues such as *CP*-violating observables. In the last few years the focus has been on the longitudinal polarization fraction f_L. This is naively expected to be close to 1.0 since spin-flip arguments indicate that the transverse polarization is of the order $m_V^2/m_B^2 \sim 0.04$. The measurement of f_L for the $B \to \phi K^*$ decays is now known to be near 0.5 with an uncertainty of about 0.04 [22, 23]. This appears to be unique to decays dominated by penguins, though the exact mechanism is still not understood despite dozens of theory papers offering Standard Model [24] or non-SM explanations [25].

In the following sections we describe a series of measurements from *BABAR* for several of these vector-vector decays. In addition see the *BABAR* measurements of branching fraction and polarization for the $B^+ \to \rho^+\rho^0$ decay are described in the talk by Christos Touramanis at this conference.

6.1. Vector-vector decays involving ω mesons

BABAR has recently submitted for publication an analysis of $B \to VV$ decays where one of the vector mesons is an ω [26]. Unbinned ML fits are performed, with the following variables in the fit: m_{ES}; ΔE; resonant masses (ω, K^* or ρ); the ω, ϕ, ρ or K^* helicity angle; and a Fisher discriminant similar to that used for the $B \to \eta' K^*$ analysis. The results of this analysis are summarized in Table II. Again the f_0 channel is included since it shares a common $\pi^+\pi^-$ final state with ρ^0. The only channel with a significant yield is $B^+ \to \omega\rho^+$. For this case, the longitudinal polarization fraction and charge asymmetry $\mathcal{A}_{ch}$ are also measured. For the $B^0 \to \omega K^{*0}$ and $B^0 \to \omega\omega$ decays, where there are signal yields of about 50 events, f_L is left free in the fit (though since this is not considered a measurement of f_L, no systematic error is given). For the other channels, f_L is fixed to the approximate expected value and varied by 0.3 to obtaining systematic errors. Belle has not yet reported searches for these decays.

If the ωK^* channels were dominated by penguin diagrams, the branching fraction would be expected to be one-half of the branching fraction of $B^+ \to \rho^+ K^{*0}$ (see next section) or $\sim 5 \times 10^{-6}$. This seems unlikely given the measurements shown in Table II. This suggests that the (Cabibbo-suppressed) tree amplitude for the ωK^* decays may not be negligible. This would indicate the possibility for measuring a large value of $\mathcal{A}_{ch}$ once these decays are observed.

6.2. $B \to \rho K^*$

The various charge states of $B \to \rho K^*$ are interesting since some are known to have significant branching fractions and f_L can be measured to compare with ϕK^*.

6.2.1. $B^+ \to \rho^+ K^{*0}$

The decay $B^+ \to \rho^+ K^{*0}$ is particularly interesting since it is thought to be a pure penguin (there is no tree diagram for this decay). In addition to the interest in the polarization, a recent paper [27] has suggested that the branching fraction and f_L from this decay can be use to limit the penguin uncertainty for the measurement of the CKM angle α in the decay $B^0 \to \rho^+\rho^-$.

BABAR has a new measurement for this decay, using a ML analysis with inputs m_{ES}, ΔE, ρ and K^* masses, the ρ and K^* helicity angles, and a neural-net variable analogous to the Fisher discriminant event-shape variable used in other *BABAR* analyses. The $K^+\pi^-$ decay used to reconstruct the $K^*(892)$ also has peaking at higher mass due to a combination of $K_0^*(1430)$ and nearby non-resonant S-wave signal. A $K\pi$ mass range extending to 1.5 GeV is used to determine the amount of S-wave signal, while a more typical narrow mass range is used for the main $K^*(892)$ analysis. These regions are shown in the “sPlots” [28] of Fig. 8 where the plot indicates the wide ranges used and the arrows indicate the narrow ranges. The signal plot in the top left shows that the S-wave $K\pi$ signal is substantially larger than the $K^*(892)$ signal. There is no evidence for contributions other than ρ^+ in the $\pi^+\pi^0$ invariant mass. In Fig. 9 we show the $B^+ \to \rho^+ K^{*0}$ signal of $\sim$210 events with the m_{ES} and ΔE projection plots for the nominal mass region. The measured branching fraction is $(10.0\pm1.7\pm2.4)\times10^{-6}$, $f_L = 0.53\pm0.10\pm0.06$, and $\mathcal{A}_{ch} = -0.01\pm0.15\pm0.01$. The first two are in good agreement with the published Belle measurement [29] (Belle has not yet measured $\mathcal{A}_{ch}$). The value of f_L is in good agreement with the value for ϕK^* as expected for pure penguin decays.

6.2.2. $B^+ \to \rho^0 K^{*+}$

The decay $B^+ \to \rho^0 K^{*+}$ is less clear theoretically because there is a (Cabibbo-suppressed) tree diagram which contributes in addition to the penguin present for all $B \to \rho K^*$ decays. It is more difficult experimentally since the branching fraction is smaller (as for $B \to \omega K^*$, it would be suppressed by a factor of two if penguin amplitudes were the only ones contributing).

BABAR has a new measurement for this channel. Both the $K^{*+} \to K\pi^0$ and $K^{*+} \to K_S^0\pi^+$ channels are used. In this case there are complications for both the $K\pi$ and $\pi^+\pi^-$ mass distributions. The former has the same $K\pi$ S-wave contributions as the previous analysis, while for $\pi^+\pi^-$, there are contributions

Table II Quantities measured in the *BABAR* ωX analysis. Measured branching fraction $\mathcal{B}$, significance S (with systematic uncertainties included), 90% C.L. upper limit, measured or assumed longitudinal polarization, and charge asymmetry $\mathcal{A}_{ch}$.

Mode	$\mathcal{B}$ (10^{-6})	S (σ)	$\mathcal{B}$ U.L.(10^{-6})	f_L	$\mathcal{A}_{ch}$
ωK^{*0}	$2.4 \pm 1.1 \pm 0.7$	2.4	4.2	$0.71^{+0.27}_{-0.24}$	—
ωK^{*+}	$0.6^{+1.4+1.1}_{-1.2-0.9}$	0.4	3.4	0.7 fixed	—
$\omega \rho^0$	$-0.6 \pm 0.7^{+0.8}_{-0.3}$	0.6	1.5	0.9 fixed	—
ωf_0	$0.9 \pm 0.4^{+0.2}_{-0.1}$	2.8	1.5	—	—
$\omega \rho^+$	$10.6 \pm 2.1^{+1.6}_{-1.0}$	5.7	–	$0.82 \pm 0.11 \pm 0.02$	$0.04 \pm 0.18 \pm 0.02$
$\omega\omega$	$1.8^{+1.3}_{-0.9} \pm 0.4$	2.1	4.0	0.79±0.34	—
$\omega\phi$	$0.1 \pm 0.5 \pm 0.1$	0.3	1.2	0.88 fixed	—

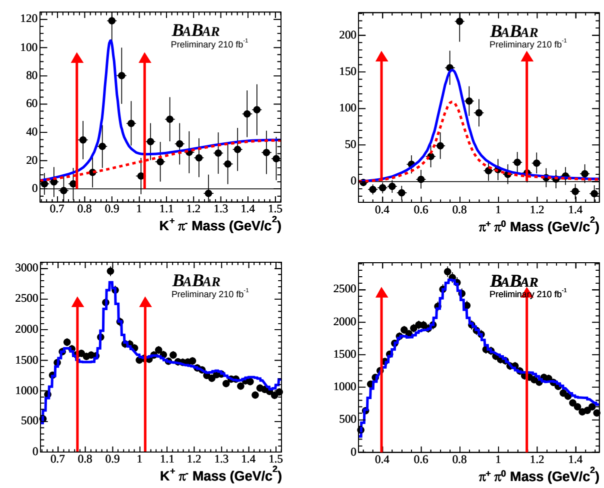

Figure 8: For the $B^+ \to \rho^+ K^{*0}$ analysis, "sPlots" of the $K^+\pi^-$ mass (left) and $\pi^+\pi^0$ mass (right) for signal (top) and $q\overline{q}$ background (bottom). The blue solid curves represent the full signal or background components and the red dashed curve indicates the contribution from S-wave $K\pi$. The plot range is for the wide fit region, while arrows indicate the nominal fit range.

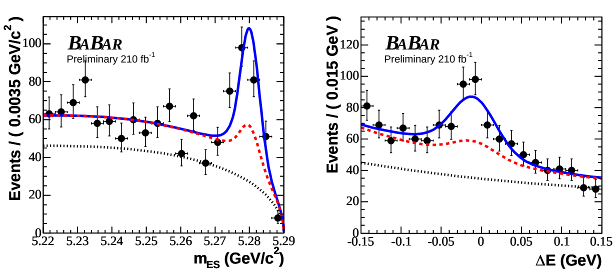

Figure 9: Projection plots of the $m_{\rm ES}$ and ΔE distributions for the $B^+ \to \rho^+ K^{*0}$ analysis. The black dotted lines show the $q\overline{q}$ background component, the red dashed lines indicate the full background component including $K\pi$ S-wave, and the blue solid line is for the full fit with the signal component.

for $f_0(980)$ and $f_0(1370)$. In Fig. 10, we show projec-

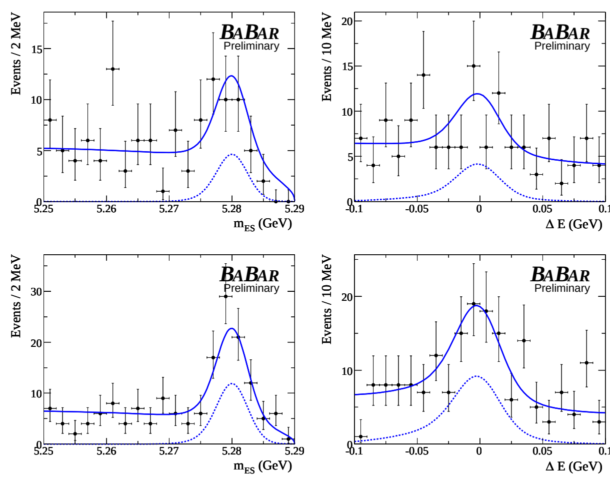

Figure 10: Projection plots of $m_{\rm ES}$ (left) and ΔE (right) for the $B^+ \to \rho^0 K^{*+}$ (top) and $Bp \to f_0 K^{*+}$ (bottom) samples. The dotted lines show the signal fit component while the solid lines are the full fit projection including signal and background.

tion plots for the $Bp \to \rho^0 K^{*+}$ and $Bp \to f_0 K^{*+}$ signals. The decay $Bp \to f_0 K^{*+}$ is observed for the first time with about 40 signal events in each K^{*+} decay channel and a fit significance of 5.0σ including systematic uncertainties. The measured branching fraction is $(5.2 \pm 1.2 \pm 0.6) \times 10^{-6}$ and $\mathcal{A}_{ch} = -0.34 \pm 0.21$. The significance for the decay $B^+ \to \rho^0 K^{*+}$ is only 2.6σ. The branching fraction is $(3.6 \pm 1.7 \pm 0.8) \times 10^{-6}$ leading to a 90% C.L. upper limit of 5.9×10^{-6}. The value of f_L determined by the fit is $f_L = 0.91^{+0.22}_{-0.20}$ though this is not considered a measurement for this decay since the signal itself is not significant. Belle has not yet reported measurements for these decays.

7. $B^0 \to a_1^+ \rho^-$

Since the decay $B^0 \to a_1^+ \pi^-$ has been observed with a branching fraction of about 40×10^{-6} [30, 31] (see contribution by Christos Touramanis to this conference), it seems likely that the branching fraction for the $B \to a_1\rho$ decays might also be large. *BABAR* has recently submitted for publication a search for the decay $B \to a_1^+\rho^-$ [32]. They find no significant signal and measure a 90% C.L. upper limit of 61×10^{-6}.

8. $B^+ \to \omega K^+$, $B^0 \to \omega K^0_S$, and $B^+ \to \omega\pi^+$

An updated analysis of the decays $B^+ \to \omega K^+$, $B^0 \to \omega K^0_S$, and $B^+ \to \omega\pi^+$ was recently submitted for publication by *BABAR* [33]. The results for the time-dependent *CP* asymmetry have been presented by Matt Graham at this conference. The branching fractions, significance, and charge asymmetries are given in Table III. These measurements supersede previous *BABAR* measurements and are in good agreement with the most recent results from Belle [34]. The results are also in reasonable agreement with theoretical expectations.

Table III Measured branching fraction $\mathcal{B}$, significance S (with systematic uncertainties included), and charge asymmetry $\mathcal{A}_{ch}$ for the decays $B^+ \to \omega K^+$, $B^0 \to \omega K^0_S$, and $B^+ \to \omega\pi^+$.

Mode	$\mathcal{B}$ (10^{-6})	S (σ)	$\mathcal{A}_{ch}$
$\omega\pi^+$	$6.1 \pm 0.7 \pm 0.4$	10.8	$-0.01 \pm 0.10 \pm 0.01$
ωK^+	$6.1 \pm 0.6 \pm 0.4$	13.0	$0.05 \pm 0.09 \pm 0.01$
ωK^0	$6.2 \pm 1.0 \pm 0.4$	8.6	—

9. Conclusions

We have reported many new measurements, mostly for rare charmless B-meson decays. Particularly noteworthy are the first observation of the decay $B \to \eta' K^*$ with the resulting constraints on possible singlet diagrams and $1/m_b$ terms in QCD factorization and the many new results for B decays to pairs of vector mesons. The latter are helping in the understanding of the small value of f_L for $B \to \phi K^*$ and are helping to reduce the penguin uncertainties for the measurement of α in $B^0 \to \rho^+\rho^-$ decays.

Acknowledgments

We thank Chris Hearty and the rest of the organizing committee for a very interesting and enjoyable conference. We also are grateful for helpful discussions with Michael Gronau, Harry Lipkin, Jon Rosner, and Jure Zupan.

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